Understanding Tubes, Transistors, and ICs

They're at the heart of any piece of radio equipment...those components that amplify signals to levels usable for communications: tubes, transistors, and integrated circuits. Here's a look at "How They Work," along with a project using a classic VHF/UHF tube from the past.

Are you ready for more "how it works" discussions and hands-on practice you can use for many years hence, friends? Shall we also include another quick-brew project for additional fun and enticement? Well, that's precisely what's lined up for this month, and the combination promises to be a winner from any angle.

This time, our main focus is on tubes and transistors, those heartbeat-of-electronics components making up the gear we all use for both local and long-range communications. Background information for this study was included in our last few months' columns, incidentally, so I'll assume you've read or reviewed them and continue on from that point without backtracking. This will hopefully keep us focused on how modern transceivers and accessories work.

Before advancing to that high-tech level, however, we need to understand the basic operational concepts of components used in today's gear. Let's begin with a quick and simple explanation of tubes and transistors (plus ICs and microprocessors), then delve further into technical aspects and applications of each. Once armed with that basic knowledge, we can pursue a variety of homebrew projects with technical know how and confidence on our side. Read close and let's get started.

Photo A. Over the years, vacuum tubes have been made in an endless array of types and have been used in all areas of amateur radio. So much so, in fact, that collecting tubes is now a big-time interest. Shown here are seven decades worth of tubes. These include (clockwise from 9 a.m.) a WE-211, 245, 3-500Z, 6146, and an 811A.

Opening Views

Vacuum tubes have been made in a wide variety of types and styles (see Photo A). Basically, they all operate on the principle of *thermionic emission* (emission of electrons from a heated object), with concentric elements surrounding a center filament, as illustrated in Figure 1a (Figure 1b shows the schematic, or symbolic, representation of the same device. Voltage applied to the filament causes it to become a red hot heating element and emit electrons that travel outward toward the tube's plate. If a tube's filament is its only electron emitter, it's called a *directly heated tube*; if a tube's filament heats a separate electron-emitting metal wrapper around it (a *cathode*), it's called an *indirectly heated tube*. Still with us? Let's continue.

Assuming a second, higher voltage is applied between a tube's filament or cathode and its plate or *anode* (and on through an external circuit), current can flow in the second circuit. In this case, the tube acts as a diode—a rectifier or a detector. If a mesh or grid of fine wire is added between the tube's filament/cathode and anode (plate), the tube becomes an *electron valve* with its flow of electrons controlled by an external voltage impressed on that grid—a *triode*. Including additional grids in tubes accelerates the flow of electrons, cancels out inter-electrode capacity, minimizes secondary emission, etc. These multielement tubes serve numerous special functions, which

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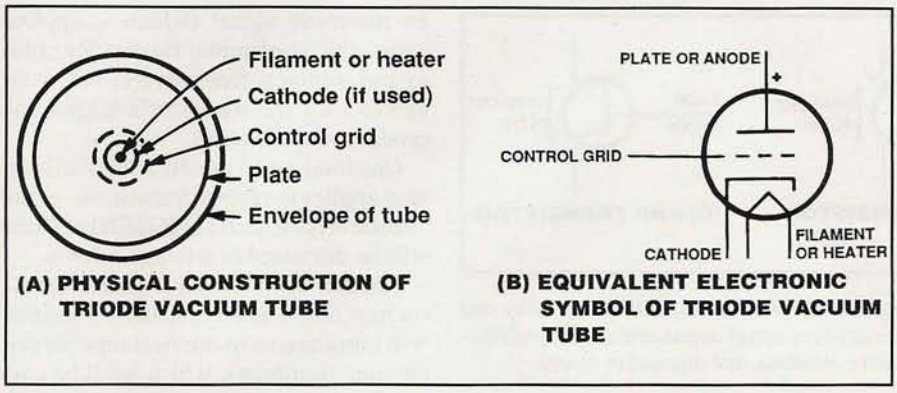

Figure 1. Physical construction/placement of elements in a triode vacuum tube as viewed from the top (A), and equivalent electronic symbol (B). Multigrid tubes have additional grids between cathode and plate. The grid closest to the cathode or filament is always the control grid.

we'll discuss later on, and carry special designations like pentodes, tetrodes, and heptodes (and no, that is not a frog wearing cool sunglasses).

Transistors are superseding vacuum tubes in numerous applications today, but tubes are still popular because they're rugged, economical, and have very high power-handling abilities. As many musicians and entertainers also know, tubes give a special full-bodied and robust sound unobtainable with transistors. Technically speaking, they produce *even*-harmonic distortion, which is pleasing to the ear, while transistors produce *odd*-harmonic distortion, which is interpreted by the brain as brash or irritating.

Transistors might easily be visualized as miniature equivalents to triode tubes, or as three-wire/element versions of those famous galena "crystal detectors" of yesteryear. In fact, internal views of early *point-contact type* transistors actually looked like tiny crystal diodes with two wires (rather than one) touching the semiconductor's surface.

Their crude design proved quite fragile, however, and soon evolved into modern *junction types* made by sandwiching tiny pieces of specially "doped" silicon or other semiconductor material, as illustrated in Figure 2a. "Doping" a semiconductor adds impurities that makes it either give off electrons (N-type) or accept them (P-type). The makeup of layers in a transistor "sandwich" determines whether it's an NPN- or PNP-type device. Both types serve the same general purpose of acting like a tiny electron valve. They just have reversed collector/emitter polarities and connect in opposite directions in a circuit.

Circuit connections to transistors are easy to understand if you remember two points. First, current always flows "against the arrow" (or in the opposite direction of the arrow) on its emitter (see Figure 2b). In the case of an NPN transistor, that means current coming from the negative/ground terminal or connection of a DC power source flows in the emitter, across the base, out the collector, and back to the positive DC connection. Second, this "negative emitter and positive collector" arrangement is similar to a tube's "negative cathode and positive plate" setup and that makes it easy to visualize if you already understand how tubes work.

ICs and Microprocessors

Integrated circuits, or *IC*s are also very popular solid-state devices today. In simple terms, they contain a group of transistors within a small package. Ah, but some ICs also contain diodes, resistors, and capacitors, you say. True! Typically, they use specially made emitter/base junctions of transistors (and ignore their collectors) to produce those components in ICs—mainly because they're smaller and less expensive to produce than discrete (separate) counterparts. There are two general families of ICs: the *analog group* used in audio and RF circuits and the *digital group* used in microprocessors and computers.

Microprocessors are made of numerous ICs on a single oversized chip (a *big* IC). Now we're really talking miniaturization and "squeezing" or "compacting." In fact, prying the top off a microprocessor and studying its innards with a magnifying glass gives the illusion of viewing a large city from an airplane flying at 20,000 feet. Microprocessors are typically used as the mathematical heart of computers and for selecting frequencies or controlling various digital-related features in transceivers. Now let's consider some interesting and useful technical aspects of tubes and transistors.

The Electron Valve Concept

Have you ever heard vacuum tubes referred to as *electron valves* and wondered about the seemingly unusual designation? Actually, the term is common reasoning and our British friends have always called tubes "valves." Why? A valve has an inlet, an outlet, and a control handle, and a tube has the comparable elements of a cathode, a plate, and a control grid. A small force applied to a valve's handle can produce a large change in its quantity of output, and a small voltage applied to a tube's grid can produce a large change in its output current. This ability to make a large reproduction of a

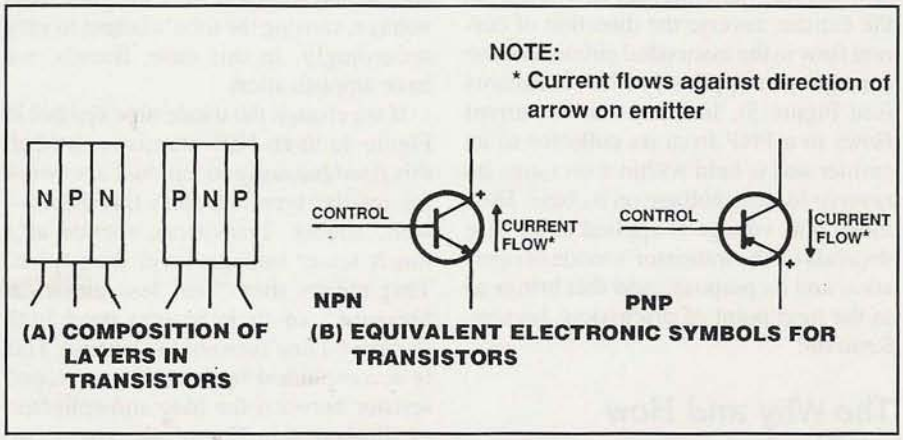

Figure 2. Physically, junction-type transistors are made by layering N- and P-type semiconductor materials (see text) as illustrated in (A). Equivalent electronic symbols for NPN and PNP transistors are shown in (B).

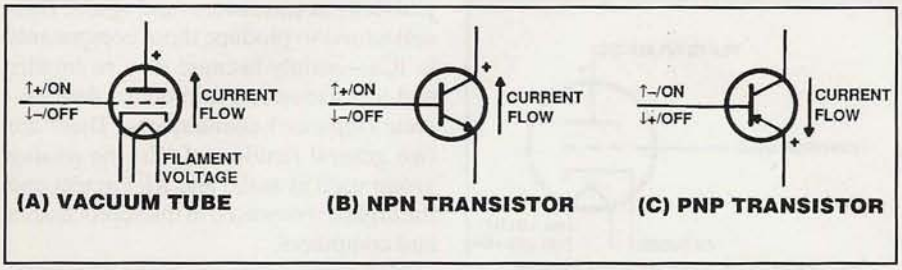

Figure 3. Vacuum tubes and transistors operate like electron valves, with the polarity and amount of voltage applied to their grid or base controlling on/off action and quantity of electrons flowing from their negative to positive elements. See discussion in text.

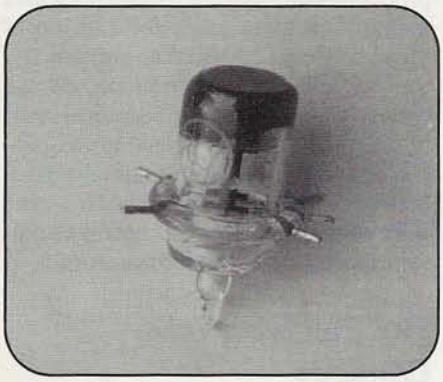

Photo B. One of the very first VHF/UHF/microwave tubes was this collector's pride RCA 955 "acorn tube." The item is still plentiful today, but you'll have to diligently search.

much smaller control signal forms the basis of what we call *amplification*.

If we consider NPNs, this valve concept can also be applied to transistors. That is, current enters at the emitter, it is varied from "full off" to "full on" by a very minute voltage applied to the base, then a larger reproduction of that signal is taken from the collector. Got that? OK, now reverse the polarities of voltage on the emitter, reverse the direction of current flow in the associated circuit, and the concept also applies to PNP transistors (see Figure 3). In other words, current flows in a PNP from its collector to its emitter and is held within a set range by *reverse biasing* voltage on its base. How much bias voltage is applied to its base depends on the transistor's mode of operation and its purpose...and that brings us to the next point of discussion: *biasing*. Read on!

The Why and How of Biasing

If a vacuum tube or a transistor is to function as an electron valve rather than just an on/off switch, it must be capable of accurately controlling current flow between its negative and positive elements. This force-controlling technique requires some assistance, which we call *biasing*. Using the familiar analogy of a water valve, you can think of biasing as a tensioning spring on the handle so it rests at a specific point and is easy (rather than difficult) to turn in either direction from that set point.

As discussed earlier, vacuum tubes require a relatively high amount of voltage or electrical pressure for operation. As a result, a small amount of "hold back" bias or negative voltage must be maintained on the tube's control grid to avoid a "full plate current" or "saturated" condition. This bias voltage can be set by a battery (not too feasible for long-term use) or by a resistor connected between a tube's control grid and ground, as illustrated in Figure 4a. Technically speaking, the ratio or values of the grid and cathode resistors establish how negative the grid is with respect to the cathode, but let's keep this simple. An incoming signal (which is AC and alternates between negative and positive polarities) then adds to and subtracts from the grid's bias voltage, causing the tube's output to vary accordingly. In this case, friends, we have amplification.

If we change the triode tube symbol in Figure 4a to an NPN transistor symbol, this *fixed biasing* concept will also work for regular type (*bipolar*) transistors—well, almost. Transistors operate at a much lower voltage level than tubes. That means they "feel less electrical pressure," so their base(s) need both reverse (-) *and* forward (+) biasing. This is accomplished by including a second resistor between the base and collector, as illustrated in Figure 4b. These two base resistors also form a voltage divider to "center the base," so to speak, with proper voltage. Then, again like a tube, an incoming signal (which is applied across the base/emitter resistor R1) adds to and subtracts from reverse bias voltage to vary the transistor's output and produce amplification.

One final point: our NPN/PNP discussion applies to regular transistors, not to "exotic" types, such as MOSFETs. Those will be discussed in a future column.

Another form of bias is *grid leak bias* (or *base leak bias* for transistors), and that will introduce us to our next topic of discussion: oscillators, which we'll be covering over the next two months. Enough theory for now, however. Let's take a break and quickly highlight a neat homebrew project with special ties to our previously discussed topics. After all, such fun pursuits are what keep ham life interesting, right?

Acorns Alive—A High-Sensitivity FSM

One of the most basic yet popular pieces of test equipment used with any and all types of amateur radio setups is a *Field Strength Meter* (FSM), a device which measures the intensity of a radio signal in the air. After using an FSM to make a couple of reference measurements, it proves handy for quick-rechecking to ensure a rig's radiated signal strength is up to its usual level, for comparing a beam antenna's front-to-back and front-to-side ratios, and for much more. Even James Bond used an FSM to find hidden spy transmitters or "bugs" in the movies.

What else can I say except that going through ham life without an FSM is like going through a day without a wristwatch. Yes, and our featured FSM is special in several ways. It is extra sensitive for checking weak signals or evaluating antenna radiation patterns from a fair distance away, it uses a classic-collectible "acorn"-type vacuum tube as shown in Photo 2 (one of the first tubes made especially for VHF and UHF, I might add), and it illustrates the technical concepts we've been discussing. This FSM circuit can also be quickly modified down the line to make a flea-power oscillator/transmitter.

Space is now tight, so read closely as we pack the following sentences with info galore! The circuit diagram of our "955FSM," plus a handy tube pinout guide, is shown in Figure 5. Basically, it works as follows: First, C1 matches or peaks an incoming signal to L1 which, in

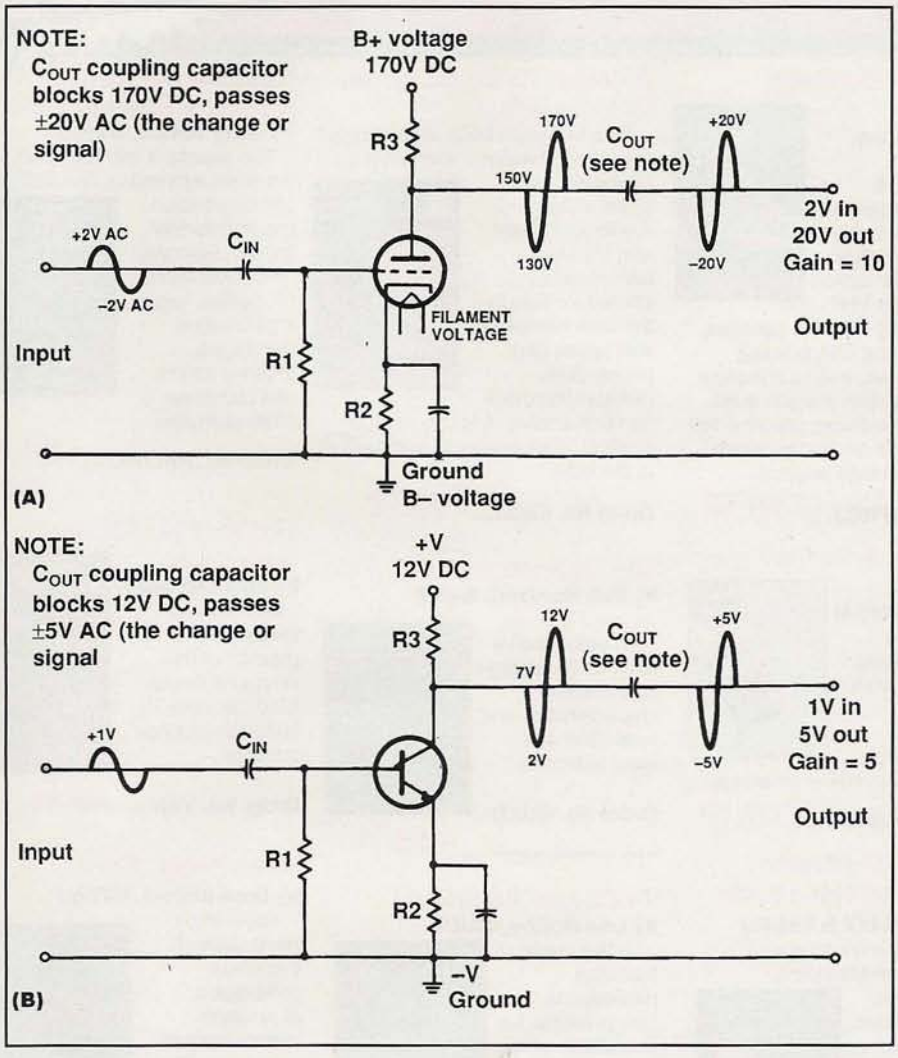

Figure 4. A bare-bones tube-type amplifier circuit (A) and the equivalent circuit using an NPN transistor (B). An incoming AC signal passes through C_{in} and is developed across R1. This varies the tube's/transistor's bias which, in turn, varies voltage drop across R3. That change in voltage is coupled through C_{out} and yields an amplified copy of the input signal.

turn, is tuned to your desired frequency by C2. The signal is then applied to the 955 acorn tube's control grid, which is biased right at the point of plate current cutoff by R1. Notice this clever point, friends. Not only does the wiring scheme for R1 vary cathode-to-plate voltage on the 955, it also ensures that the grid is always fixed-biased *more negatively* than the cathode—a prerequisite to cutting off plate current flow. A detected or incoming signal causes current to flow in the 955 (linearly, according to signal strength, rather than logarithmically, like a regular diode detector, I might add), and resultant strength/plate current is read on the meter.

As you probably surmised, homebrewing authentic classic gear of any type is quite different from quick-assembling a similar item from junkbox parts. Indeed, many of the components are genuine collectibles and are often priced accordingly. How much is that? There are no set guidelines here. I can only say pay what you feel comfortable paying and the seller feels comfortable accepting. Check hamfest fleamarkets and well-known dealers of classic parts such as Fair Radio and Antique Electronic Supply (see "Resources") for 955 tubes, their center mounting sockets, old-style trimmer capacitors, and a meter. A 100-, 200- or 500-microamp full-scale meter is ideal; 1-milliamp meter is OK if slightly less sensitivity is acceptable. Build a working showpiece! Make your friends green with envy!

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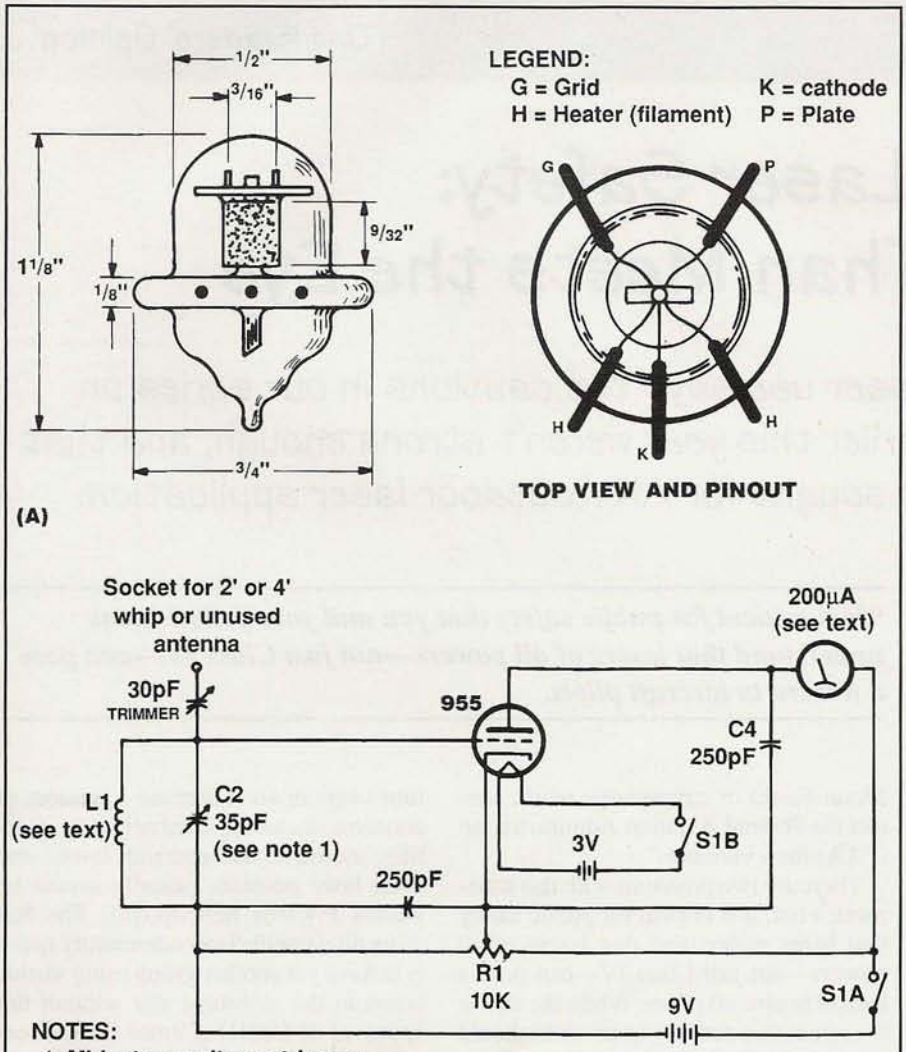

Figure 5. Pinout of the classic 955 "acorn tube" (A) and circuit diagram of the acorn tube field strength meter (B).

Original coil data for this FSM covered only 50 to 80 MHz (seven turns of number 14 enamel-coated wire wound open air style with a diameter of 1/2 inch and stretched to a length of 1 inch). Rewinding that coil for a total of only three turns, however, should extend the FSM's range to 150 MHz and higher. Finally, I should note that 9 volts is a very low plate potential, even for a little 955 (its maximum is 150 volts). In the linear amplifying detector setup, however, it is ideal. If desired, you might try series-connecting two 9 volt-batteries for even higher sensitivity. The tradeoff will be slightly less meter linearity.

Oops! We're totally out of space and must sign off for now. Stay tuned for more theory and fun projects in coming months. Next, we plan to spotlight oscillators and, believe it or not, a home-reproducible 1936 transceiver. 73,

—Dave, K4TWJ

Resources

Fair Radio Sales, 1016 E. Eureka, P.O. Box 1105, Lima, OH 45802; Phone: (419) 227-6573

Antique Electronic Supply, 6221 S. Maple Ave., Tempe, AZ 85283; Phone (602) 820-5411

On the Cover

"Weak signal is my main interest," says Francis "Shep" Shepard, W7HAH, of Stevensville, Montana, "whether it's EME or terrestrial, meteor scatter or aurora, whatever...." A ham for over 60 years, Shep says he started out on the old 5-meter band in the 1930s, but that it was his work as an air traffic controller that got him into VHF and UHF weak-signal operating. "We were hearing Chicago O'Hare's tower on 125 MHz in June, back in the 1960s, and I also saw reflections on radar—up in the gigahertz range—from ground clutter and rain up to 200 miles away. That kind of sparked my interest....When I retired in 1975, I really got into weak-signal, building my own antennas, etc."

Shep says he's worked 88 countries on 2 meters, mostly off the moon, along with all 50 U.S. states. On 432 MHz, he's worked 47 states and 41 countries; and on 6 meters, he has six countries, including the first-ever single-Yagi-to-single-Yagi EME contact with Europe—a station in Sweden, back in 1983 or 84. Speaking of Yagis, Shep has one 11-element M^2 Yagi on 6 meters; four 19-element KLM Yagis on 2 meters; and an array of 12 homebuilt 24-element Yagis on 432 MHz. Also visible in the cover photo is a dish for 1296 MHz, but he's been unable to get it put up and on the air.

The biggest change he's seen in his 61 years in amateur radio, says Shep, is that hams in general no longer build their own equipment. We're going into another change now, he added, "into computers and...seeing new types of communication, like high-speed CW on meteor scatter. It's probably not bad," notes Shep. "It makes for a very interesting hobby. We have quite a choice." (Cover photo by Larry Mulvehill, WB2ZPI)